Pressure-Gradient Induced Incipient Motion

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ABSTRACT:

Our shorelines and beaches evolve with forcing conditions present in near shore environments. This morphologic evolution results from the spatial gradients of the sediment flux. Traditional theories for sediment transport rely on incipient motion being induced by wave driven shear stress as derived by Shields (1936)[3] . These theories do not always account for the unsteady flows present in a coastal environment. To better understand the foundation for incipient motion in the near shore environment, the validity of these theories were evaluated under different field-scale applications. Specifically two theories were examined, the Shields parameter and a new theory by Sleath (1999)[4], which, until recently, has only been evaluated in limited laboratory environments. The Sleath theory diverges with the theory presented by Shields in that it relies on a pressure gradient to induce incipient motion of sediment. To gain a better understanding of the mechanics and conditions for incipient motion of sediment, the goal of this research was to evaluate both shear and pressure gradient induced sediment transport in a large-scale wave flume.

INTRODUCTION:

The coastal environment represents an immediate need in engineering. Although a relatively new and developing field, coastal engineering is and will become more and more important in today's ever-growing society. According to Dalrymple (2001)[1], the anticipated tripling of imported cargo by 2020 will require expanded harbor facilities and deeper navigational channels in increased wave climates. A limiting constraint in coastal design is an inability to accurately predict the transport of sediment in these environments. Sediment transport represents the integration of small forces applied to individual grains and can have very large and consequential results. In order to help predict and respond to the potentially devastating impacts that the movement of sand can have over a large area, a more accurate understanding of the small-scale trigger mechanisms of sediment transport must be developed. This research, using a newly developed instrument that measures bed thickness through electrical resistance, examines two methods for the incipient motion of sediment.

Traditionally, the method used to parameterize sediment transport involves the Shields parameter, commonly used in steady flow such as rivers. This dimensionless parameter represents the ratio of the destabilizing forces caused by the shear stress gradients to the stabilizing force applied by gravity. It is given by,

$$\theta = \frac{d\tau_b/dz}{(\rho_s-\rho)g} = \frac{\tau_b}{(\rho_s-\rho)gd_{50}} \qquad (1)$$

with τ_b being the applied bed stress, ρ_s the sediment density, ρ the density of water, **g** is gravity, and d_{50} is the grain size diameter. Theta is used to represent the dimensionless Shields parameter. In this theory, the driving force behind the primary movement of sediment is a critical bed shear stress that is applied as the passing wave moves across the sediment layer. When this critical bed shear stress is exceeded, ($\theta_{crit} \approx 0.04$), incipient motion of the sediment occurs. The near bed sediment concentration is often parameterized as a function of the excess stress. When the stress increases further small scale bed forms such as ripples are washed out and a thicker mobile bed layer develops. This thicker mobile bed layer is defined as sheet flow and is a flat blanket of moving sand [Dean and Dalrymple, 2002]. This research only looks at the mechanisms for incipient motion and ignores the resulting effects and causes for sheet flow. While Shields theory presents valid explanations for incipient motion of sediment in steady flows, one of the problems is that it does not account for the unsteady dynamics present in wave environments such as the near shore.

An alternative theory presented by Sleath, assumes that in some oscillatory flow environments, sediment transport can be induced by pressure gradients. The Sleath parameter represents the ratio of destabilizing forces applied by the horizontal pressure gradient to the stabilizing gravitational forces. It is given by

$$\mathbf{S} = \frac{\mathbf{dp/dx}}{(\rho_s-\rho)\mathbf{g}} = \frac{\mathbf{du/dt}}{(\rho_s-\rho)\mathbf{g}} = \frac{\rho \mathbf{U_o} \omega}{(\rho_s-\rho)\mathbf{g}} \qquad \mathbf{(2)}$$

where ω is the angular wave frequency and $\mathbf{U_o}$ is the velocity amplitude. S is used to represent the dimensionless Sleath parameter. As with the Shields parameter, when the Sleath parameter exceeds a critical value, **$S \approx 0.2\sim0.29$,** under field and laboratory conditions respectively, incipient motion can occur. The difference between the Shields and Sleath parameter, lies in what is the driving force behind the cause of incipient motion in the seabed. While the Shields parameter relies on a critical shear stress applied by the onshore and offshore movement of the waves over the bed to make it mobile, the Sleath parameter is controlled by the horizontal pressure gradient produced during the oscillatory movement of the wave's trough and crest over the seabed to induce motion. When exceptionally large waves pass over the seabed, the increased difference in pressure at the sediment layer is enough to initiate movement of the sand particles and start incipient motion of the bed.

Until recently there have been little, if any, qualitative field experiments to validate theories pertaining to pressure gradient induced sediment transport. While there have been observations made to validate these theories, they have been limited to experimental oscillatory tunnels. To better understand the full effect of sediment transport on beach morphology, there needs to be a more defined evaluation of the small-scale mechanics that drive this process. Two problems that hamper this evaluation are the lack of control over field conditions and the ability to quantitatively observe the bed reaction under the differing wave conditions. With the newly developed instrument RBES, standing for Rapid Bed Elevation Sensor, which measures bed thickness via electrical resistance; and the simulation of field-scale conditions at the O.H. Hinsdale large wave flume, this research attempted to accomplish this.

METHODS:

In order to make observations of pressure-gradient induced incipient motion, an understanding must be made of where it is taking place. To accomplish this, an evaluation of the critical Shields and Sleath parameters was made using velocity data obtained from the Acoustic Doppler Velocimeter (ADV) at different positions in the surf zone. By substituting

$$\tau_b = \rho U_*^2 \tag{3}$$

into equation 1,

$$\theta = \frac{U_*^2}{(s-1)gd_{50}} \tag{4}$$

is derived, which allows the critical Shield parameters to be evaluated. This same U_* value was then used to calculate the critical Sleath parameters using equation 2. These values were collected for multiple wave heights and period combinations including 30, 40, 50, and 60 cm wave heights and 4, 6, and 8 second periods. This process was done at various positions in the flume in order to determine whether shear-based or pressure-gradient induced incipient motion of the sediment was taking place. After evaluating these values and comparing them to each other, a decision was made as to where either form of incipient motion of the sediment was taking place. By determining these values at various positions in the surf zone, the best location to examine the sediment layer for incipient motion was determined. After evaluating the results, it was determined that the best chance of experiencing pressure-gradient incipient motion was at Bay 8 or 64.54 m in the x-direction of the wave flume.

RBES, as mentioned earlier, is a ground-breaking instrument constructed by research engineer Gabe Smith of the Ohio State Uninversity. It is based off of an apparatus that was developed under F. de Rooij et al (1998)[2] at the University of Cambridge. Using an AC electrical source to prevent polarization, a current is passed through the water column and sediment layer using two electrodes at a sampling rate of 16.7 microseconds. The electrode placed in the water column is referred to as the reference electrode and the one buried in the sediment is the working electrode. The current passes through a wheatstone bridge circuit with two fixed resistors of 10 ohm apiece. The third and fourth resistors are variable with the fourth being a function of the sediment thickness and an assumption that the water column has zero resistance. A 16-channel analog multiplexer rests between the working electrode and the wheatstone bridge. The voltage over the wheatstone bridge is amplified to increase the signal and rectified to a direct current. After passing through a filter to remove any noise from the rectifier, the signal is read using an analog-to-digital converter (ADC) on a data acquisition board in the PC. **Fig. 1**[2] provides a diagram of the RBES bridge circuit and its connections.

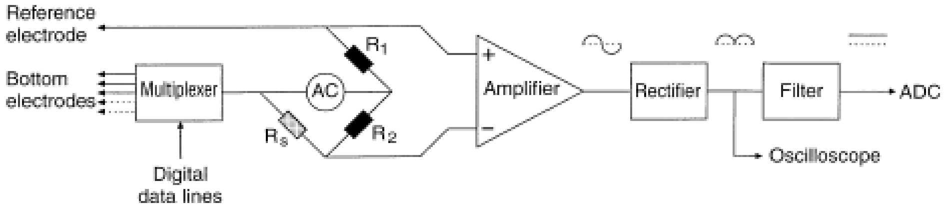

Fig. 1

As RBES is a newly developed instrument, a complete calibration was needed to determine the variable resistance of the third resistor, the resistance levels responding to the sediment layer depth, and the burial depth of the working electrode. To accomplish this task the working electrode was placed at the bottom of a large tank filled with the same water that was used to fill the large wave flume. After completing the circuit with the reference electrode, located 31 cm above the working electrode, a layer of sediment, 1 cm in thickness, was placed above the working electrode. Then multiple resistance settings were used to test the layer of sediment's resistance for a time series of one minute. This process was repeated for the increasing thickness of the sediment layer at 1 cm increments. Upon completion, 13 different data sets were created with each varying by the resistance of the third resistor.

To analyze this data, a program in MATLAB was written that evaluated the mean voltage of the 32 outputs of each reading from the circuit. These averages were then plotted against the corresponding sediment thickness to which they were measured. After evaluating these graphs, the decision was made about which resistance to use for the variable resistance of the wheaststone bridge. This decision was based off of the linearity of the graphs because of the consistency to which the corresponding sediment thickness could be measured. The resistance setting of 500 ohm was chosen for the variable resistor based off of this required condition. Also based off of this graph, a burial depth of 11 cm in the bed was chosen for the working electrode.

The next step upon the completion of calibrating RBES was its deployment into the flume. With Sleath values greater than the critical values needed for the instigation of pressure-gradient induced incipient motion, Bay 8 was the chosen as the burial point. Under the guidance of Gabe Smith, the first step in this process was a hole that was dug in the sediment bed and next to the flume wall. This was done so that an anchor could be placed underneath the working electrode in the chance that the bed eroded underneath it and moved elsewhere due to the prolonged wave conditions. To accomplish this, a stinger was threaded into the flume wall at 19 cm below the surface of the bed level and 8 cm below the resting point for the working electrode. This allowed the needed 11 cm of bed depth above the sensor. Plastic ties were then used to connect the working electrode to the stinger and sediment was backfilled underneath the electrode to provide a level surface as well as to fill in the 11 cm above. The reference electrode was then placed 21 cm above the bed by attaching it to the flume wall via a large screw. This was done to represent the conditions present in the tank used for calibration. Using this set up, data was collected for different wave conditions. These wave conditions included 30, 40, 50, and 60 cm wave heights with 4 sec wave periods as well as 40 cm wave heights with 7 sec wave periods.

RESULTS:

After recording velocity data from the ADV for wave heights of 30, 40, 50, and 60 cm and differing wave periods of 4, 6, and 8 sec; the Shields and Sleath values were calculated and plotted (y-axis) verse the cross-shore distance (x-axis) for which they were measured. The results were plotted by wave height so that a comparison could be made as to where the critical values under both conditions were being met. The following figures, **Fig. 2** and **Fig. 3**, depict the dimensionless Shields and Sleath parameters respectively, for a wave height of 50 cm.

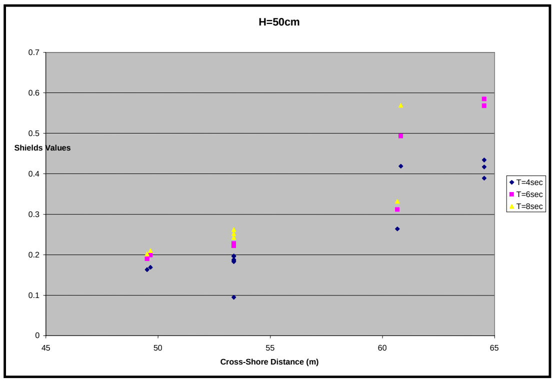

Fig. 2

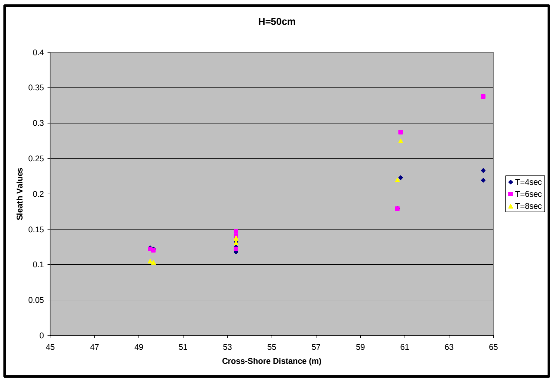

Fig. 3

In **Fig. 2**, the Shields values fail to reach critical values above 0.8 at any location in the flume. This is not the same situation for the Sleath values which, at around Bay 9 or x ≈ 61m, begin to reach and exceed the critical value of 0.2 for pressure-gradient induced incipient motion to take place. This pattern holds true for all of the wave heights tested. Based off of these graphs and the location of Sleath values exceeding critical values, a decision was made to position RBES at Bay 8.

The calibration of RBES was done prior to its deployment into the large wave flume. After recording voltage levels at one minute intervals for each 1 cm layer of sediment addition, the data was processed and plotted for each variable resistance level. This gave 13 different graphs to evaluate with voltage being plotted under units of mV in the y-axis and sediment thickness being plotted in the x-axis in units of cm. The following graph , **Fig. 4**, depicts the results for the 500 ohm resistor that was chosen after evaluating all 13 resistor settings and the linearity each graph possessed.

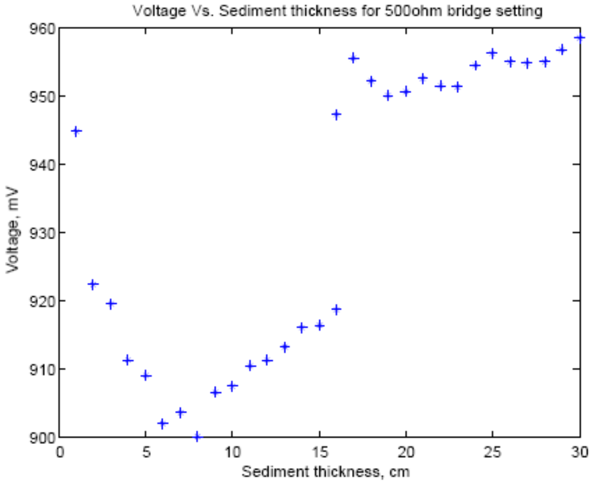

Fig. 4

In **Fig. 4**, a linear connection can be seen between the 6 cm and 16 cm layer of sediment thickness. The calculated slope of this line is 1.80mV/cm. At the 16 cm layer, a drastic increase and jump in voltage is experienced and the linearity of the graph is greatly decreased. After evaluating the 12 other graphs for the different resistor settings, the resistance setting was chosen to be 500 ohm based from the results above.

Once the location for deployment was chosen and the calibration was complete, RBES was buried in the sediment bed. This was done at Bay 8 to ensure that the measurement of incipient motion of the sediment could be the result of a pressure-gradient. The wave conditions used included 30, 40, 50 and 60 cm wave heights with 4 sec wave periods. This data was collected in the same fashion as the calibration runs but the voltage was plotted as a time series instead of sediment thickness. **Fig. 5** and **Fig. 6,** are the results of the runs for a wave height of 30 cm and 60 cm respectively.

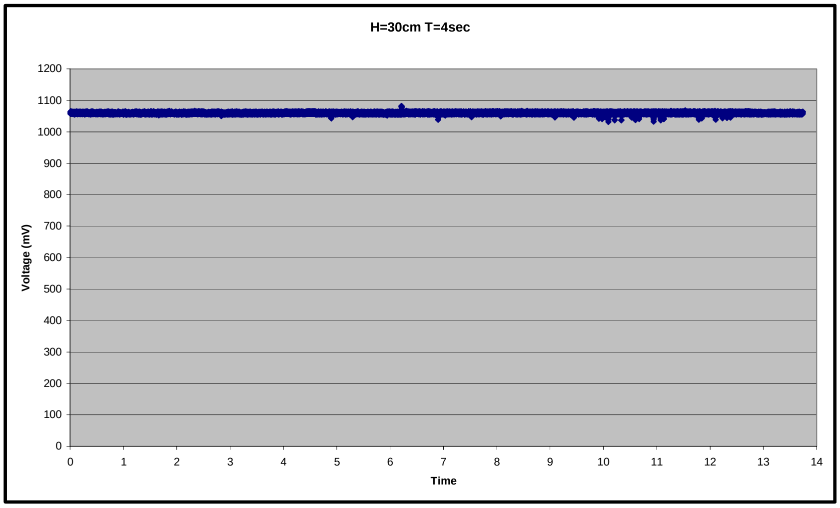

Fig. 5

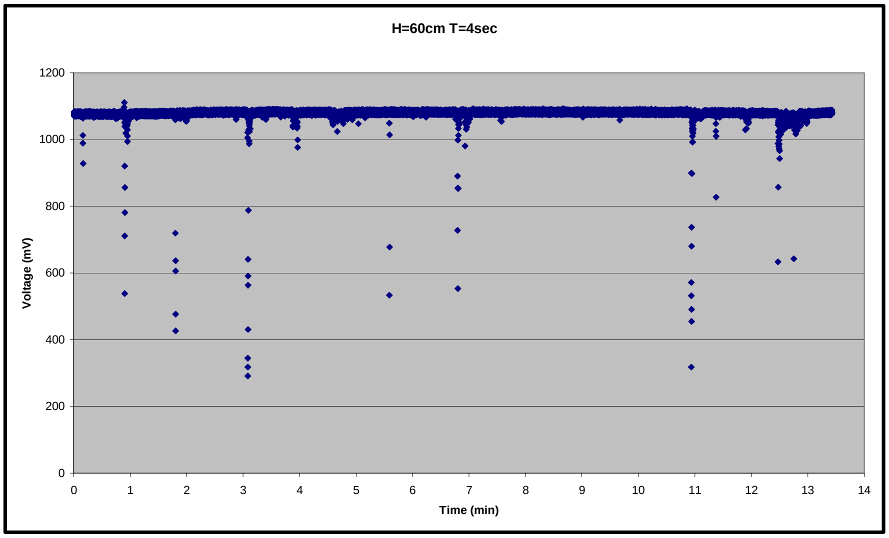

Fig. 6

The results of these graphs show that a distinguished voltage drop occurs throughout the 14 minute time series in both wave runs. The voltage drops are more visible and frequent during the run of wave height 60 cm but are still visible, particularly at the end, during the run of wave height 30 cm. An average voltage value during the 60 cm run came out to 1076.153 while the average voltage value during the 30 cm run was 1058.903. After evaluating a particular dip in voltage at 12.38 minutes into the 30 cm run, an average voltage reading of 1051.006 mV for this was recorded. This dip consisted in a 7.897 mV difference between the average voltage values for the entire run. Using the voltage to sediment thickness scale that was created during the calibration of the instrument, this dip equated to a 4.34 cm increase in bed depth. Under the same analysis for the 60 cm run, the dip at 4.59 minutes into the run, an average voltage value of 1060.769 was recorded. The difference between the average values for the entire run and this dip equated to 15.384 cm leading to a 8.45 cm increase in bed depth. These increases in bed depth are for the specified dips in voltage at the given time and not representative of the whole data record.

DISCUSSION:

The results of the calculated Shields and Sleath values show that there is a distinct point in the wave flume where pressure-gradient incipient motion of the sediment can potentially be occuring. This can be seen by the values for the Sleath parameter exceeding the critical value of $S \approx 0.2$, needed for field conditions, at 64.54 m in the x-direction of the flume. While this is where RBES was placed in order to measure the particular increases in bed depth due to pressure-gradient induced incipient motion, it must also be noted that the Shields values are still greatly exceeding the set critical value of $\Theta \approx 0.08$, needed for incipient motion. Based on this fact, the results of the data gathered by RBES could indicate either shear-based or pressure-gradient incipient motion.

Upon examining the results from the calibration of RBES, a rather large jump in voltage is seen between the 16 and 17 cm layers. This jump corresponds to a stoppage in data acquisition that lasted approximately 12 hours. The tank was filled immediately prior to calibration and the temperature of the water used to fill the tank was well below the average temperature of the lab. After sitting for 12 hours in the lab, the increased water temperature led to increased voltage values as the resistance of water is inversely related to water temperature. Also, upon further analysis of the calibration process, the calibration was done in an opaque horse trough and the reading of the sediment thickness was done at an angle 35 cm above the top of the bed. This could have resulted in skewed results for the voltage readings corresponding to the bed depths and could be the cause for the decreased linearity of the graph between 0-5 cm and 17-30 cm.

The resulting graphs from the analysis of the data collected from RBES, **Fig.5** and **6**, show positive results for measured increases in bed depth. This can be seen by the pattern of voltage dips that occur throughout the time series. Even more positive results, indicating pressure-gradient induced transport of sediment, are shown by the decreased number of voltage dips seen in the graph of a run with 30 cm wave heights, **Fig. 5**. This corresponds to the theory presented by Sleath where the increased difference between the crest and trough of the passing wave leads to an increased pressure-gradient and in turn the initiation of incipient motion and transport of sediment. In the 30 cm run, the occurrence of pressure-gradients large enough to cause incipient motion of sediment should occur less because the number of large waves is decreased. During the 60 cm run the opposite is the case due to the increased number of waves with larger wave heights.

While the results from the data collection of RBES show promise in the description of bed depth, there were a couple of factors that could have contributed to inaccurate data. It was observed that many of the waves were breaking directly overtop the burial spot. This obviously could have skewed the results, as the bed was violently changed due to the force of the crashing wave. Another factor that could potentially have negatively affected the results is the cloud of suspended sediment that was often seen hovering directly above the burial location of RBES. This cloud of sediment was the result of the crashing waves located both beyond (in the onshore location) and at the burial location. The cloud of sediment suspension could have skewed the results because of the increased resistance that it would have brought to the column of water that was being examined. In calibration of the instrument, a pure water column was used and the addition of suspended sediment to this column should have resulted in higher voltage readings. Fortunately the averaged voltage readings from both sets of wave runs, 30 and 60 cm, coincide with this. The averages, 1058.903 for 30 cm and 1076.153 at 60 cm, are higher than the expected ceiling value of 920 mV that was determined during calibration.

CONCLUSION:

Specification of the exact location and conditions under which critical values of both Shields and Sleath parameters were being exceeded was in line with what was expected. Under all wave conditions the critical Shields value (**$\theta_{crit} \approx 0.04$**) was exceeded but the critical Sleath value (**$S \approx 0.2$**) was only exceeded at around Bay 8 of the wave flume. This was expected as the shoaling of the waves created an increased difference between the crest and trough that allowed for the possibility of pressure-gradients large enough to induce incipient motion of the sediment. While the graphs of this data indicate this possibility, they also show that the conditions favorable to shear-based incipient motion are still viable at all positions of data collection. This is a very critical point of confusion in this research. To counter this unpredictability, as to which method of incipient motion is taking place, a more in-depth analysis of the pressure-gradients in the same time series as the measure of bed depth would be needed. The benefits that this would bring to the results would be evident by the fact that a correlation could be made between an increase in bed depth and measured pressure gradients.

The calibration of RBES was a success in the fact that a linear relation was found between the sediment thickness and the corresponding voltage readings. Unfortunately this was not the case throughout the complete 30 cm range of thickness values. Fortunately the probability, that these results were skewed by error in the execution, is high. The lack of visibility in examining the sediment depth could possibly be rectified by using a transparent calibration tank. Another part of the calibration process that could be executed differently is the temperature difference that occurred during the 12 hour period difference between measuring the 16 cm and 17 cm sediment layers. This could have been avoided by performing all sediment layer measurements in succession. Also, part of the problem with this part of the calibration process is that the water used was not at room temperature when the calibration process started. As this process is time-consuming, a gradual increase in water temperature occurred throughout. A substantial increase in water temperature between the first measurement and the last could have lead to an inaccurate voltage reading for sediment thickness.

Even with the problems that were encountered in data acquisition, the cloud of suspended sediment and waves breaking at the burial point, the deployment of RBES was a complete success. With this being the first field-test of its capabilities, RBES performed up to expectations. While the results of the data that was collected from RBES, are not completely conclusive, they are still hopeful for the future. The results show distinct voltage drops across the time series. Although the exact cause of these voltage drops cannot be confirmed and is assumed to be the product of pressure-gradient induced incipient motion, the fact that they appear is a strong indication that incipient motion is taking place. Future improvements and experimentation with RBES will only result in more accurate data collection.

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BIOGRAPHY:

I stem from the heart of it all in Columbus, Ohio. This is my current home as well as the home of my university, the Ohio State University. My major is Civil Engineering with an emphasis in the environmental discipline. Future plans include employment involving some facet of Civil Engineering and graduate school after a preferred type of work is determined.